

Research Progress and Applications of Surfactants for Sensitive Skin

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Abstract. Sensitive skin, affecting nearly half of the global population, is characterized by heightened reactivity to environmental and cosmetic stimuli, leading to discomfort and a compromised skin barrier. Surfactants, essential components in skincare products, play a significant role in both the irritation and protection of sensitive skin due to their interactions with the skin's lipid layers. This paper explores the characteristics of sensitive skin and the impact of various surfactants—anionic, cationic, amphoteric, and non-ionic—on skin health. Advancements in surfactant design, including natural surfactants, green chemistry approaches, and molecular modifications, are discussed to highlight their potential in reducing irritation and enhancing skin compatibility. The study concludes that surfactant innovation, driven by molecular design and the incorporation of environmentally friendly processes, holds great promise for developing high-quality products that meet the specific needs of sensitive skin while promoting sustainable development in the cosmetics industry.

Keywords: Sensitive skin, surfactants, skincare application.

1. Introduction

In 1987, Maybach introduced the term "cosmetic intolerance syndrome" to describe the condition of sensitive skin, characterized by clinical symptoms such as stinging, tightness, itching, and burning, often accompanied by capillary dilation, dryness, and flushing [1]. These symptoms cause considerable distress to individuals with sensitive skin, potentially impacting their quality of life. Epidemiological studies reveal a high global prevalence of sensitive skin, affecting approximately 50% of the population. In China, about 40.8% of the population is affected, with a higher incidence among women than men [2]. Consequently, addressing and treating sensitive skin has become a priority in dermatological research, with many individuals turning to skincare products for relief.

Surfactants are substances that, even in small amounts, significantly alter the interfacial properties of solution systems [3]. Due to their unique structure, surfactants can self-assemble or form nano-scale aggregates with other components, such as liquid crystals, microemulsions, and vesicles [4]. They exhibit surface activity by absorbing at the gas-liquid interface, reducing the surface tension of water, and at liquid interfaces, decreasing the interfacial tension between oil and water [5]. Surfactants play a key role in skincare products, functioning as emulsifiers, thickeners, detergents, and foaming agents [6]. However, some surfactants can disrupt the skin's microbiome by interacting with proteins and lipids in the epidermis, leading to allergic reactions and irritation, particularly in sensitive skin [7].

This paper examines the characteristics and specific needs of sensitive skin, reviews the classification and application of surfactants in cosmetics, and explores future research directions aimed at developing surfactants that are compatible with sensitive skin types.

2. Characteristics and Needs of Sensitive Skin

2.1. Physiological Characteristics of Sensitive Skin

Sensitive skin is a complex condition marked by heightened reactivity to external stimuli, such as cosmetics, temperature fluctuations, and pollutants. Common symptoms include burning, itching, erythema, and stinging [8]. A key feature of sensitive skin is the compromised skin barrier, primarily consisting of the stratum corneum and lipids. This impaired barrier function results in increased

transepidermal water loss, making the skin more vulnerable to external irritants [9]. Additionally, sensitive skin may be linked to heightened sensitivity in the nervous system, where an elevated release of neurotransmitters from nerve endings further amplifies the skin's reactivity [10].

2.2. Special Requirements for Surfactants

The needs and reactions of sensitive skin to surfactants are distinct from those of normal skin. It has been shown by studies that the natural barrier function of the skin can be easily damaged by traditional strong surfactants, such as SLS (sodium lauryl sulfate), leading to increased water loss and inflammation, particularly in the case of sensitive skin. Furthermore, it is understood that gentle, non-ionic, or amphoteric surfactants are more appropriate for use on sensitive skin [11].

3. Classification of Surfactants and Their Applications in the Cosmetic Industry

Classification of surfactants is typically based on their ability to dissociate into ions in water and the charge of those ions [12]. The main categories include anionic, cationic, amphoteric, and non-ionic surfactants.

3.1. Anionic Surfactants

Anionic surfactants, when hydrolyzed in water, generate amphiphilic anions, including compounds such as alkyl sulfates, lauryl sulfates, and fatty acid salts [13]. These surfactants are known for their strong cleaning properties, but their high cleaning ability can disrupt the structure of the stratum corneum, increasing trans epidermal water loss and making the skin more vulnerable to external irritants [14]. The length and chemical structure of the carbon chain in anionic surfactants play a crucial role in determining their potential for skin irritation. Studies show that surfactants with either shorter or longer carbon chains tend to be less irritating, whereas those with medium-length chains may cause greater damage to the skin barrier [15]. To address these concerns, Lechuga et al. [16] introduced low-toxicity silica nanoparticles into anionic and non-ionic surfactants. The results indicated that the inclusion of nanoparticles enhanced surfactant stability and, when forming spherical core-shell structures, significantly reduced skin irritation.

Teng et al. [16] modified TiO₂ NPs with APTES and 1H, 1H, 2H, 2H-perfluorooctyltriethoxysilane (POTS) and coated the modified TiO₂ NPs onto the surface of paper using epoxy resin (EP) as an adhesive to create a superhydrophobic coating. The coating exhibited a water contact angle (WCA) of $153 \pm 1.5^\circ$ and a water sliding angle (WSA) of $3.5 \pm 0.5^\circ$. Additionally, the superhydrophobic coating demonstrated excellent mechanical stability, maintaining a WCA above 150° after being soaked in strong acid and strong base for 96 hours and stored at room temperature for six months, as shown in Figure 1. These results indicate that the superhydrophobic coating possesses durability and robust hydrophobic properties.

3.2. Cationic Surfactants

Cationic surfactants are composed of a hydrophobic group attached to a positively charged hydrophilic group, with their counterions typically being simple, non-surfactant anions [17]. In aqueous solutions, these surfactants dissociate into positively charged cations, which can strongly interact with the negatively charged lipid layers and proteins on the skin's surface through electrostatic interactions. This interaction aids in cleaning, dirt removal, and moisturizing [18]. Bujak et al. [19] investigated the impact of amphiphilic cationic polymers, such as cationic derivatives of guar gum, on the safety of bath cosmetic products. Their study revealed that incorporating cationic guar gum derivatives into bath products, even at low concentrations, significantly reduced skin irritation. At a concentration of 0.5%, a decrease of approximately 35% in the corn alcohol-soluble protein value was observed compared to samples without the added cationic polymers, indicating a reduction in potential skin irritation.

3.3. Amphoteric Surfactants

Amphoteric surfactants contain both cationic and anionic hydrophilic groups within their molecular structure, enabling them to both accept and donate protons [20]. Based on the structure of the cation, amphoteric surfactants can be categorized into several types, including amino acid-based, betaine-based, amidoamine-based, imidazoline-based, and lecithin-based surfactants [21]. These surfactants are known for their excellent stability and high resistance to both acidic and basic substances, maintaining their surfactant properties over a wide pH range [22]. Melby et al. [23] reported the use of ampholytic copolymers, specifically acryloyloxyethyl trimethyl ammonium chloride combined with methacrylic acid or 2-acrylamido-2-methylpropanesulfonic acid (AMPS), in hair care, styling, and skincare products at concentrations as low as 0.01%. Their inclusion significantly reduced skin irritation and minimized scalp damage, highlighting their suitability for sensitive skin formulations.

3.4. Non-ionic Surfactants

Non-ionic surfactants are distinguished from ionic surfactants by their inability to dissociate into ions in aqueous solutions. Consequently, the presence of acids, bases, or salts does not significantly affect them, but they are soluble in aqueous or organic solvents [24]. Furthermore, non-ionic surfactants are endowed with excellent wetting and cleaning functions, exhibit a certain tolerance to hard water, and can be used in combination with other ionic surfactants, making them an essential component in formulations for emulsifiers and detergents [25].

4. Mechanism of Surfactants' Impact on Sensitive Skin

4.1. Structure of Surfactants and Skin Compatibility

The unique properties of surfactants are defined by their molecular structure, which includes a non-polar, lipophilic tail and a polar, hydrophilic head, irrespective of the surfactant type (as depicted in Figure 1) [26]. The extent to which these two components can damage the skin barrier is directly influenced by their characteristics. For example, the adsorption and penetration abilities of the surfactants on the skin are determined by the length and degree of saturation of the hydrophobic chain, whereas the interaction of the surfactant with the skin's lipid bilayer is influenced by the type of hydrophilic head group.

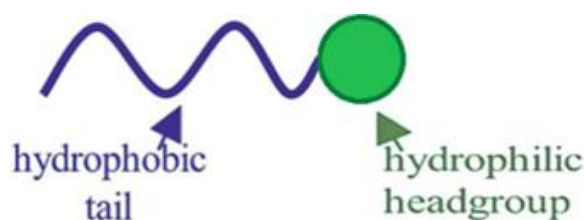


Fig. 1 Schematic diagram of a surfactant monomer [26]

The varying degrees of biocompatibility exhibited by different hydrophilic head groups (such as sulfonate, carboxylate, amide, etc.) when interacting with skin cells are observed. It is noted that surfactants with sulfonate groups are generally found to be more irritating than those with carboxylate groups, as sulfonate groups are capable of more easily penetrating the skin's stratum corneum and binding with proteins in the skin, which can lead to inflammatory responses. Conversely, surfactants with amide groups are often considered to be gentler and more suitable for use on sensitive skin [27].

4.2. Mechanisms of Surfactant Irritation and Evaluation Methods

The potential harm of surfactants to sensitive skin is evaluated through various testing and assessment methods developed by scientists. These tests are designed to simulate real usage conditions and enable the comparison of the irritancy of different surfactants by means of quantifiable indicators.

The Draize test, a classic method for assessing skin and eye irritation, typically involves the direct application of surfactants onto animal skin to observe local reactions such as redness, swelling, and erosion [28]. However, due to ethical concerns regarding animal experimentation, the Draize test has been gradually replaced by some in vitro skin models.

In vitro skin models are designed to mimic the structure and function of human skin, offering a more humane and efficient tool for assessing the irritation potential of surfactants. Through these models, the skin irritation of surfactants can be assessed under laboratory conditions, thereby avoiding the ethical dilemmas associated with animal experiments [29].

TEWL (transepidermal water loss) serves as a commonly used indicator for evaluating skin barrier function. The application of surfactants may result in an increase in TEWL, causing skin dehydration and sensations of dryness and stinging. Consequently, the monitoring of changes in TEWL values is considered an important criterion for evaluating the irritancy of surfactants [30].

4.3. Mechanisms of Surfactant Irritation and Evaluation Methods

Allergic reactions and discomfort in sensitive skin may be induced by surfactants through the triggering of immune responses and the causing of inflammatory reactions. The understanding of the allergenic mechanisms of surfactants aids in explaining their impact on sensitive skin and offers a theoretical basis for the selection of safer products.

Upon penetration of the skin barrier by surfactants, binding with keratinocytes or immune cells within the skin may occur, triggering a response from the immune system. For example, the activation of dendritic cells by certain surfactants can induce T cell-mediated allergic reactions, leading to symptoms such as skin redness and itching [31].

The release of histamine by surfactants may be induced by damaging the mast cells in the skin. Histamine, as a key mediator in allergic reactions, causes skin vasodilation and increased vascular permeability, leading to symptoms such as itching and swelling in sensitive skin [32].

5. Renovative Sufactants

5.1. Innovation and Development of Surfactants Friendly to Sensitive Skin

Natural surfactants, particularly those extracted from plants and marine organisms, have gradually emerged as a popular choice for sensitive skin care due to their mildness and biodegradability. They are characterized by a natural mildness that causes less irritation to the skin and can also degrade quickly in the environment, thereby reducing the ecological burden [33]. The application of sophorolipids in sensitive skin care products has been extensively studied, demonstrating their ability to maintain the skin's moisture balance while cleaning, without easily causing irritation. Surfactants derived from protein sources, such as those from silk and collagen, have been found to possess very high biocompatibility. Upon contact with the skin, these surfactants do not disrupt the natural structure but instead enhance the skin's moisturizing function [34].

A safer care option for sensitive skin is offered by natural surfactants, characterized by their gentle, non-toxic, and biodegradable properties, and they demonstrate good potential in terms of ecological sustainability.

5.2. Green Chemistry Surfactants

As environmental protection awareness grows, there is a trend towards the development of surfactants based on green chemistry synthesis. The core concept of green chemistry aims to achieve product sustainability by reducing the use and generation of harmful substances. Consequently, an increasing number of surfactants are being produced using green synthesis methods, which not only lower the carbon footprint during production but also exhibit excellent mildness and biodegradability.

Ionic liquids are a class of green chemical materials characterized by their unique properties. In recent years, surfactants derived from ionic liquids have attracted attention due to their low toxicity and high efficiency. These surfactants are capable of effectively reducing skin irritation and also

possess outstanding wetting properties and biodegradability, positioning them as potential choices for future sensitive skin care products.

5.3. Molecular Design and Modification of Surfactants

The mildness of surfactants has been enhanced through molecular design and modification, which has become a significant direction for innovation in surfactant development in recent years. Alterations to the molecular structures of surfactants have been made by researchers to optimize their physicochemical properties, with the aim of reducing skin irritation.

Polyethylene glycol (PEG) modification, a common method of molecular modification, can significantly enhance the mildness of surfactants. The combination of the hydrophilic end of the surfactant with PEG reduces direct contact between the surfactant and the skin, thereby lowering skin irritation. Moreover, PEG modification can improve the moisturizing effect of the product, making it more suitable for sensitive skin [35].

Block copolymers, which are polymers formed by chemically bonding different types of monomers, can enhance the performance of surfactants by adjusting intermolecular interactions. For instance, some block copolymer surfactants can provide gentle cleaning and moisturizing effects simultaneously, making them an ideal choice for sensitive skin [36].

Nanotechnology has introduced new opportunities to the development of surfactants. The interaction of nanoscale surfactants with the skin at a smaller molecular level significantly reduces the coefficient of friction and minimizes physical skin irritation. Additionally, nanosurfactants can enhance wettability to improve the cleaning effect of products, avoiding the excessive irritation caused by traditional surfactants [37].

6. Conclusion

Surfactants, serving as core ingredients in skincare and cleaning products, have a significant role in the research field of sensitive skin care. In recent years, as consumers have increasingly demanded mildness and safety, researchers have conducted in-depth studies on the molecular structure of surfactants, methods of irritation testing, and their allergenic mechanisms in sensitive skin. This article has offered a basic overview of the characteristics of sensitive skin and the structure and classification of surfactants, and has introduced common irritation testing methods for surfactants, with a detailed analysis of the allergenic mechanisms. Overall, the research and development of surfactants friendly to sensitive skin is not only a scientific challenge but also a commercial opportunity. It is expected that through continuous innovation in molecular design, green chemistry, and natural extracts, more high-quality products that meet the needs of sensitive skin will be developed in the future, promoting the sustainable development of the industry.

The application of cationic surfactants in sensitive skin care currently still faces issues with irritation. Future research should concentrate on the development of more gentle molecular structures to reduce damage to the skin barrier. Adjustments to the chain length or polar groups could be made to decrease irritation while maintaining cleaning and moisturizing functions. Additionally, with the advancement of biotechnology, future research on cationic surfactants could utilize techniques such as microbiomics and genomics to study the relationship between sensitive skin and skin microbiota. The development of surfactants that can regulate the skin's microbiome balance could emerge as a new research direction.

References

- [1] Martins M S, Ferreira M S, Almeida I F, et al. Occurrence of Allergens in Cosmetics for Sensitive Skin. *Cosmetics*, 2022, 9 (2): 32.
- [2] Lu Nan, Wu Min, Song Jiao, et al. Overview of Sensitive Skin and Advances in Medical Aesthetic Treatments. *Journal of Tissue Engineering and Reconstructive Surgery*, 2023, 19 (03):323-328.

- [3] Wang C, Zhang P, Chen Z, et al. Effects of fatty acyl chains on the interfacial rheological behaviors of amino acid surfactants. *Journal of Molecular Liquids*, 2021, 325: 114823.
- [4] Wang D, Xiao Z, He J, et al. Strong Synergistic Molecular Interaction in Catanionic Surfactant Mixtures: Unravelling the Role of the Benzene Ring. *Langmuir*, 2023, 39 (36): 12649-61.
- [5] Guerrero-Hernández L, Meléndez-Ortiz H I, Cortez-Mazatan G Y, et al. Gemini and Bicephalous Surfactants: A Review on Their Synthesis, Micelle Formation, and Uses. *International Journal of Molecular Sciences*, 2022, 23 (3): 1798.
- [6] Yang Zeyu, Tai Xiumei, Liu Huimin, et al. Application of Surfactants in Cosmetics. *Detergent & Cosmetics*, 2019, 42 (10):50-55.
- [7] Ben Ammar A, Ben Ali M, Cherif B, et al. Lactiplantibacillus plantarum OL5 biosurfactants as alternative to chemical surfactants for application in eco-friendly cosmetics and skincare products. *Bioprocess and Biosystems Engineering*, 2024, 47 (7): 1039-56.
- [8] Wang X, Su Y, Zheng B, et al. Gender-related characterization of sensitive skin in normal young Chinese. *Journal of Cosmetic Dermatology*, 2020, 19 (5): 1137-42.
- [9] Lodén M. Role of Topical Emollients and Moisturizers in the Treatment of Dry Skin Barrier Disorders. *American Journal of Clinical Dermatology*, 2003, 4 (11): 771-88.
- [10] Misery L, Sibaud V, Merial-Kiney C, et al. Sensitive skin in the American population: prevalence, clinical data, and role of the dermatologist. *International Journal of Dermatology*, 2011,50 (8): 961-7.
- [11] Ananthapadmanabhan K P, Moore D J, Subramanyan K, et al. Cleansing without compromise: the impact of cleansers on the skin barrier and the technology of mild cleansing. *Dermatologic Therapy*, 2004, 17(s1): 16-25.
- [12] Kashif A, Rehman R, Fuwad A, et al. Current advances in the classification, production, properties and applications of microbial biosurfactants - A critical review. *ADVANCES IN COLLOID AND INTERFACE SCIENCE*, 2022, 306.
- [13] Koleva Y, Barzilov I. Potential ecological risk associated with presence of anionic surfactants in the environment. *Journal of environmental protection and ecology*, 2021, 22 (1): 39-49.
- [14] Kubota K, Kakishita A, Okasaka M, et al. Effect of Alkyl Structure (Straight Chain/Branched Chain/Unsaturation) of C18 Fatty Acid Sodium Soap on Skin Barrier Function. *Applied Sciences*, 2020, 10 (12): 4310.
- [15] Rhein L D, Robbins C R, Fernee K, et al. Surfactant structure effects on swelling of isolated human stratum-conrneum. *Journal of the Society of Cosmetic Chemists*, 1986, 37 (3): 125-39.
- [16] Lechuga M, Avila-Sierra A, Lobato-Guarnido I, et al. Mitigating the skin irritation potential of mixtures of anionic and non-ionic surfactants by incorporating low-toxicity silica nanoparticles. *Journal of molecular liquids*, 2023, 383.
- [17] Phaodee P, Sabatini D A. Anionic and Cationic Surfactant Synergism: Minimizing Precipitation, Microemulsion Formation, and Enhanced Solubilization and Surface Modification. *Journal of Surfactants and Detergents*, 2021, 24 (4): 551-62.
- [18] Gan L X, Hao C L, Jiang X M. Controllable adsorption and desorption of a cationic surfactant at quartz directed by host-guest complex. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2021, 625: 126880.
- [19] Bujak T, Nizioł-Łukaszewska Z, Ziemlewska A. Amphiphilic cationic polymers as effective substances improving the safety of use of body wash gels. *International Journal of Biological Macromolecules*, 2020, 147: 973-9.
- [20] Sarkar R, Pal A, Rakshit A, et al. Properties and applications of amphoteric surfactant: A concise review. *Journal of surfactants and detergents*, 2021, 24 (5): 709-30.
- [21] Zhao Y, Du J, Xu Z, et al. Preparation and surface performance of new amphoteric Gemini surfactants. *Chemical Engineering of Oil and Gas*, 2022, 51 (3): 111-6.
- [22] Lipin V A, Sustavova T A, Gorkina T E. New Polyampholytes and their Capacity to Form Complexes with Amphoteric Surfactants. *Fibre Chemistry*, 2021, 53 (2): 73-5.
- [23] Melby A L , Vozza N F , Lamar R ,et al. Ampholyte polymers for use in personal care products:09/159843.US6066315 [2024-09-10].

- [24] Sun X Y, Zeng H B, Tang T. Effect of non-ionic surfactants on the adsorption of polycyclic aromatic compounds at water/oil interface: A molecular simulation study. *Journal of colloid and interface science*, 2021, 586: 766-77.
- [25] Smith O E P, Waters L J, Small W, et al. CMC determination using isothermal titration calorimetry for five industrially significant non-ionic surfactants. *Colloids and surfaces b-biointerfaces*, 2022, 211.
- [26] Ren H, Mo W X, Li B. Effect of surfactants on the cellulosic fiber characteristics during paper recycling. *Cellulose*, 2023, 30 (12): 7939-53.
- [27] Palmer T R, van der Kooij H M, Abu Bakar R, et al. How Particle Deformability Influences the Surfactant Distribution in Colloidal Polymer Films. *Langmuir*, 2022, 38 (41): 12689-701.
- [28] Xie Zhen, Huang Wei, Zhang Jinsong, et al. Study on Corneal Damage Biomarkers in the Evaluation of Cosmetic Eye Irritation. *China Surfactant Detergent & Cosmetics (Chinese and English)*, 2024, 54 (02):161-167.
- [29] Zhang Tiantian, Guo Ruimin, Zhang Linfeng, et al. Application and Research Progress of In Vitro Cell Models in Cosmetic Evaluation. *China Cosmetics Review*, 2022, (11):89-95.
- [30] Zhao Xin. Application of TEWL in the Study of Skin Barrier Function Evaluation. *Guangdong Chemical Industry*, 2014, 41 (14):133-134.
- [31] Haley K J, Ciota A, Contreras J P, et al. Alterations in lung collectins in an adaptive allergic immune response. *American Journal of Physiology-Lung Cellular and Molecular Physiology*, 2002, 282 (3): L573-L84.
- [32] Inami Y, Andoh T, Sasaki A, et al. Surfactant-induced Itching and the Involvement of Histamine Released from Keratinocytes. *Yakugaku Zasshi-Journal of the Pharmaceutical Society of Japan*, 2012, 132 (11): 1225-30.
- [33] Salati S, Papa G, Adani F. Perspective on the use of humic acids from biomass as natural surfactants for industrial applications. *Biotechnology advances*, 2011, 29 (6): 913-22.
- [34] Faivre V, Rosilio V. Interest of glycolipids in drug delivery: from physicochemical properties to drug targeting. *Expert opinion and drug delivery*, 2010, 7 (9): 1031-48.
- [35] Ke Zhongming. Research on Quality Improvement of Polyethylene Oxide Surfactant Products. East China University of Science and Technology, 2020.
- [36] Wu Ruonan. Design, Synthesis, and Application Performance of Amphiphilic Block Copolymers. Shandong University, 2023.
- [37] Korean Research Team Invents Nanosurfactant Biotechnology. *China Rural Science & Technology*, 2018, (04):12.